Latent Stereopsis for Motion in Depth in Strabismic Amblyopia

Robert F. Hess,[1] *Behzad Mansouri,*[1,2] *Benjamin Thompson,*[1,3] *and Elena Gheorghiu*[1]

Purpose. To investigate the residual stereo function of a group of 15 patients with strabismic amblyopia, by using motion-in-depth stimuli that allow discrimination of contributions from local disparity as opposed to those from local velocity mechanisms as a function of the rate of depth change.

Methods. The stereo performance (percentage correct) was measured as a function of the rate of depth change for dynamic random dot stimuli that were either temporally correlated or uncorrelated.

Results. Residual stereoscopic function was demonstrated for motion in depth based on local disparity information in 2 of the 15 observers with strabismic amblyopia. The use of a neutral-density (ND) filter in front of the fixing eye enhanced motion-in-depth performance in four subjects randomly selected from the group that originally displayed only chance performance. This finding was true across temporal rate and for correlated and uncorrelated stimuli, suggesting that it was disparity based. The opposite occurred in a group of normal subjects. In a separate experiment, the hypothesis was that the beneficial effect of the ND filter is due to its contrast and/or mean luminance-reducing effects rather than any interocular time delay that it may introduce and that it is specific to motion-in-depth performance, as similar improvements were not found for static stereopsis.

Conclusions. A small proportion of observers with strabismic amblyopia exhibit residual performance for motion in depth, and it is disparity based. Furthermore, some observers with strabismic amblyopia who do not display any significant stereo performance for motion in depth under normal binocular viewing may display above-chance stereo performance if the degree of interocular suppression is reduced. The authors term this phenomenon latent stereopsis. (*Invest Ophthalmol Vis Sci.* 2009;50:5006–5016) DOI:10.1167/iovs.09-3551

Our ideas on the nature of the binocular visual deficit in strabismic amblyopia are in a state of flux. It was once believed that observers with strabismic amblyopia lack binocular cortical mechanisms due to the effects of a binocular competitive imbalance early in life during the critical period of visual development. These ideas were based, on the one hand, on the neurophysiological finding that animals deprived by way of surgically induced strabismus early in life develop a cortex with less responsive binocular cells[1–3] and, on the other hand, the finding that observers with strabismic amblyopia do not exhibit significant binocular summation of contrast signals.[4–6] Clinically, it has been argued that observers with strabismic amblyopia are stereoblind to static disparities when tested with random dot stimuli devoid of the figural artifacts contained in some clinical stereo tests.[7] The picture was of a cortex devoid of binocular cells with the consequence of irretrievable loss of all stereo function.

We now know that not all binocular cells are affected by surgically induced strabismus early in life; binocular cells responding to motion in depth (i.e., dynamic stereo) may be spared.[8] Complimentary evidence in observers with strabismic amblyopia who are blind to static disparities shows that they can detect dynamic disparities in motion-in-depth stimuli.[9–11] Furthermore, the loss of the binocular responsiveness of cortical cells in strabismic animals is largely reversible[12] by ionophoretic applications of bicuculline (selective blocker of GABA A receptors), suggesting an active suppression rather than a loss of cellular function.[13] Furthermore, there is reason to doubt the claim that observers with strabismic amblyopia do not possess binocular mechanisms, since Baker et al.[14] showed normal binocular contrast summation in observers with strabismic amblyopia when the signal attenuation by the amblyopic eye is taken into account, suggesting that the lack of summation found previously was due to the imbalance in the monocular signals before the point of summation. Taken together, these findings suggest that observers with strabismic amblyopia do have binocular mechanisms. More recently, it has been shown that the reason that binocular combination does not normally occur for suprathreshold motion and orientation tasks in observers with strabismic amblyopia is because of interocular suppression.[15] A reduction in suppression leads to normal levels of binocular combination in these observers, revealing the presence of binocular cortical mechanisms. Thus, there is converging evidence for the conjecture that persons with strabismic amblyopia possess cortical cells with binocular connections, but that during binocular viewing suppressive mechanisms render the cortex functionally monocular. A new picture is emerging that suggests that the loss of stereo function is incomplete with some sparing for motion in depth and that it is dependent on active suppression rather than loss of cells.

In this study, we asked two questions: First, is the residual stereo function in strabismic amblyopia that has been reported for motion in depth due to preserved motion processing or to preserved disparity processing? Second, is its absence in some persons with strabismic amblyopia relative (i.e., present but unable to be used due to suppression) or absolute (not present at all)? Since most previous tests of stereo sensitivity in amblyopia involve static disparities, to obtain a more comprehensive assessment of the depth-processing capabilities of observers with strabismic amblyopia, we measured their stereo performance for stimuli moving at different rates in depth. Our stimuli were composed of dynamic random dots (a dynamic random dot stereogram or DRS) devoid of any figural clues as to depth.

From [1]McGill Vision Research, Department of Ophthalmology, McGill University, Montreal, Quebec, Canada; the [2]Division of Neurology, Department of Internal Medicine, University of Manitoba, Winnipeg, Manitoba, Canada; and the [3]Department of Optometry and Vision Science, University of Auckland, Auckland, New Zealand.

Supported by Canadian Institute for Health Research (CIHR) Grants MT108-18 and MOP53346 (RFH).

Submitted for publication February 10, 2009; revised April 1 and 28, 2009; accepted July 23, 2009.

Disclosure: **R.F.Hess**, None; **B. Mansouri**, None; **B. Thompson**, None; **E. Gheorghiu**, None

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Robert F. Hess, McGill Vision Research, Department of Ophthalmology, McGill University, 687 Pine Avenue W (H4-14), Montreal, Quebec H3A 1A1, Canada; robert.hess@mcgill.ca.

Investigative Ophthalmology & Visual Science, October 2009, Vol. 50, No. 10

Two mechanisms have been proposed for stereo motion-in-depth detection: (1) a mechanism that is sensitive to temporal changes of binocular disparity.[16–22] This mechanism first detects disparities and then computes motion in depth from its change over time. This mechanism can contribute to motion in depth in both temporally correlated and temporally uncorrelated DRSs. (2) A mechanism sensitive to interocular velocity differences[23–25]: This mechanism first detects monocular motion (velocity signals) separately in the two eyes and then computes motion in depth from the interocular velocity differences. This mechanism can contribute to motion in depth only in temporally correlated DRSs.

Our use of temporally correlated and temporally uncorrelated DRSs allowed us to determine the nature of any mechanism that supports any residual motion-in-depth stereo performance in strabismic amblyopia. If residual performance is observed only for temporally correlated DRSs then the mechanism must compute the motion in depth from a comparison of the monocular velocity signals. If similar performance is observed for both correlated and uncorrelated DRS, then a disparity-based mechanism must be responsible.

METHODS

Observers

Fifteen subjects with strabismic amblyopia were tested: The results are displayed in Table 1. All provided informed consent, in accordance with the Declaration of Helsinki.

Four of those subjects (GH, AR, AM, and KS) and four normal subjects participated in the experiment in which we examined the effects of a neutral-density (ND) filter or an interocular delay on stereo motion perception. All normal subjects had normal or corrected-to-normal visual acuity and good stereoscopic vision. Clinical details of the four amblyopic observers participating in the experiment are given in Table 1.

Stimuli and Procedure

The stimuli were DRSs consisting of red and green randomly distributed bright dots (square-like elements) on a dark background (5% dot density). The dot size was 6 arcmin. The DRSs were generated in real time on a computer (Macintosh G4; Apple Computer, Cupertino, CA), using OpenGL libraries graphic software (http://www.opengl.org/ provided in the public domain by Khronos Group, Beaverton, OR) and presented to the subjects on a monitor (1280 × 1024 pixels at 75 Hz; LaCie IV, LaCie, Hillsboro, OR). Stereoscopic vision was made possible by placing red and green filters in front of the observer's eyes so that each image was visible to one of the eyes only (light separation between red and green filters that were matched to the r and g monitor guns was better than 99%). The experiments were performed in an otherwise dark room.

Two types of DRSs were used: temporally uncorrelated and temporally correlated. The *temporally uncorrelated* DRS consisted of the ongoing alternation of two image pairs: (A, A) and (B, B) (Fig. 1a). Before each trial, the computer generated two stereograms with left and right image pairs (L, R), which we denote by (A, A) and (B, B), that were fully correlated. The patterns A and B were uncorrelated. Two disparity-defined shapes (squares) were hidden on the left and right sides of each image (Figs. 1a, 1b). Successive images contained different disparities, such that, when displayed in alternation, they resulted in a square-wave–like modulation of disparity over time. The size of the disparity-defined squares was 50 × 50 dots and the two disparities were $D_1 = 0$ arcmin and $D_2 = \pm 48$ arcmin (8 dots × 6 arcmin) crossed and uncrossed disparity. In successive

TABLE 1. Clinical Data for the 15 Amblyopic Subjects at the Initial Screening

Obs	Age/Sex	Type	Refraction	Acuity	Squint	History, Stereo
RD	49/F	LE strab	+3.25 DS +4.75-0.75×45°	20/15 20/40	XT 5°	Detected age 6 y, glasses since 6 y, no other treatment, local stereopsis (160 arc second)
MM	21/F	RE strab	ϕ ϕ	20/40 20/25	ET 5°	Detected age 5 y, patching for 1 y, recent surgery, no static stereopsis
YC	36/M	LE Strab	+2.00 DS +2.00 DS	20/15 20/40	ET 5°	Detected age 2 y, patching for 4 years, glasses for 18 y, no static stereopsis
AR*	47/M	RE strab	Plano Plano	20/20 20/50	ET 2°	Detected age 6 y, no patching, no surgery, no static stereopsis
GH*	45/M	RE mixed	−1.25-0.5×180° +1.25DS	20/20 20/63	ET 6°	Detected age 10 y, patching for 1 m, glasses for 1 y, no static stereopsis
ED	43/F	LE strab	+0.75DS +0.75DS	20/16 20/63	ET 3°	Detected age 6 y, patching for 1 y, local stereopsis (40 arc second)
PH	33/M	LE mixed	−2.00DS +0.50DS	20/25 20/83	ET 5°	Detected age 4 y, patching for 6 m; surgery age 5 y, no static stereopsis
GN	32/M	RE mixed	+5.00-2.00×120° +3.50−1.00×75°	20/70 20/20	ET 8°	Detected age 5 y, patching for 3 m, no glasses, 2 strabismus surgeries RE age 10-12, no static stereopsis
KS*	40/M	RE strab	+0.50-1.00×180° +0.50DS	20/70 20/20	EX 4°	Detected age 10 y, patching for 1 m, glasses for 1 y, no static stereopsis
SY	39/F	LE mixed	−8.00D +4.00-2.50×180°	20/20 20/70	ET 1°	Detected age 5 y, patching, no surgery, no static stereopsis
MB	50/M	RE strab	1.00 DS +1.00 DS	20/32 20/80	ET 3°	Steady central fixation, no surgery, first glasses at 32 years, no static stereopsis
ML	23/F	RE mixed	+1.0-0.75×90° −3.25 DS	20/80 20/25	ET 6°	Detected age 5 y, patching for 2 y, no static stereopsis
MG	33/F	RE strab	−0.50 DS +0.50 DS	20/100 20/15	ET 1°	Detected age 4 y, patching for 6 m, no surgery, no static stereopsis
XL	33/F	LE strab	12.50 DS 12.75 + 0.75×110°	20/20 20/400	ET 15°	Detected age 13 y, no treatment, no static stereopsis
AM*	44/M	RE strab	Plano Plano	20/20 20/600	ET 20°	Detected age 4 y, no patching, no surgery, no static stereopsis

The angle of strabismus was measured with a major amblyoscope, and stereopsis was measured with the Randot test. The squint angle is given in degrees where 1° equals 1.75 prism diopter. strab, strabismus; Mixed, strab and aniso; Sq, squint; Obs, observers; RE, right eye; LE, left eye; ET, esotropia; XT, exotropia; ortho, orthotropic alignment; DS, diopter sphere.

* Subjects who underwent a more detailed investigation.

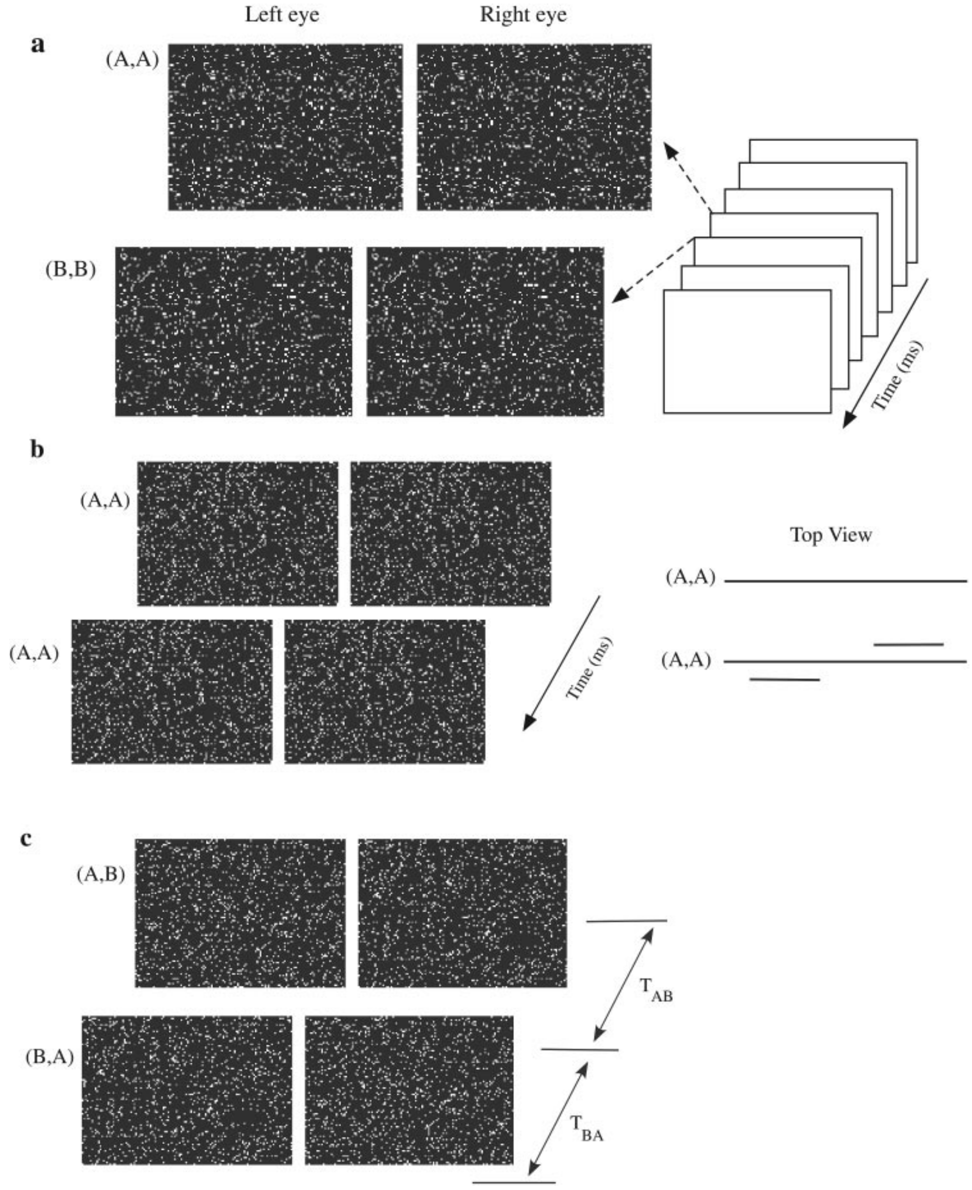

Figure 1. Stimuli used in the experiments: (**a**) *temporally uncorrelated* DRS consisting of the ongoing alternation of two image pairs, (A, A) and (B, B), each having one of two disparity values: 0 and ±48 arcmin. The patterns A and B were uncorrelated. (**b**) *Temporally correlated* DRS in which a single image pair (A, A), alternated between two disparity values: 0 and ±48 arcmin. (**c**) DRS presented with interocular delay. The stimulus (A, B), (B, A) consists of the ongoing alternation of two image pairs: (A, B) and (B, A).

images, the two squares were displaced in opposite directions in depth (i.e., one square alternated between 0 and 48 arcmin crossed disparity and the other between 0 and −48 arcmin uncrossed disparity. The *temporally correlated* DRS consisted of a single-image pair (A, A) that alternated between the two disparity values, 0 and ± 48 arcmin (Fig. 1b). Because the same textural pattern was used in the temporally correlated DRS, the disparity-defined shape steps in depth relative to a static background, whereas in temporally uncorrelated DRS, the depth of the disparity-defined square is judged in respect with a dynamic background. To make the relative depth judgments as comparable as possible for the two types of DRS, we used also a dynamic background for temporally correlated DRS (i.e., the background had a different random-dot textural pattern on every frame).

Experiment 1. We varied the presentation times of the two images in steps of 13.3 ms, between 13.3 and 226 ms. This method resulted in temporal frequencies between 37.5 and 2.2 Hz. The step size of 13.3 ms for the presentation times was dictated by the frame rate of the monitor (1/75 Hz). Different frame durations (i.e., temporal frequencies) were presented in a random order during each session. Each of the 17 temporal frequency conditions was measured 20 times.

Experiment 2. We repeated these measurements on four observers with strabismic amblyopia who exhibited chance performance in experiment 1 but with an ND filter (ND 1.00) in front of the fellow fixing eye. Similar measurements were undertaken in four normal observers.

Experiment 3. In the experiment in which we examined the effects of interocular delay, the DRSs consisted of the continuous alternation of two image pairs: image pair (A, B) and image pair (B, A) (Fig. 1c). The two alternated images were uncorrelated in two ways: spatially and temporally (i.e., the left and right images were uncorrelated at all times and also each eye's image consisted of the alternation of two uncorrelated images). The stimulus (A, B), (B, A) constituted a DRS in which correlation was 0 within each of the periods T_{AB} and T_{BA} and thus, throughout the presentation time. In this stimulus, the sequence of patterns was identical in the left and right eyes (i.e., A, B, A, B,…), but the patterns were out of phase. However, if the visual system would tolerate the delay of one eye's image by one time period, then this stimulus would become binocularly indistinguishable from the temporally uncorrelated DRS stimulus (A, A), (B, B), resulting in high correlation at all times. We varied the presentation times of the two images in steps of 13.3 ms, between 13.3 and 186 ms. This variation resulted in temporal frequencies between 37.5 and 2.6 Hz. Again, different frame durations (i.e., temporal frequencies) were presented in a random order within each session. Each temporal frequency was measured 20 times.

Experiments 1, 2, and 3. We used a forced-choice paradigm and a depth discrimination task in which the subject indicated (by pressing a key) whether the disparity-defined square in the left or in the right side of the screen was closest to him or her. The DRSs were presented on the screen until the subject gave an answer. The subjects were free to make eye movements. We used a level of 75% correct answers, indicated by a dotted horizontal line in the graph averages, as the criterion for reliable depth detection.

RESULTS

Experiment 1: Temporally Correlated and Uncorrelated Motion-in-Depth Sensitivity

From our initial screening, which involved the measurement of performance (percentage correct) as a function of the temporal frequency (or frame duration in milliseconds), we found only two subjects who exhibited above-chance performance (ED, RD). In these subjects, performance was near ceiling level and did not show any dependence on either the

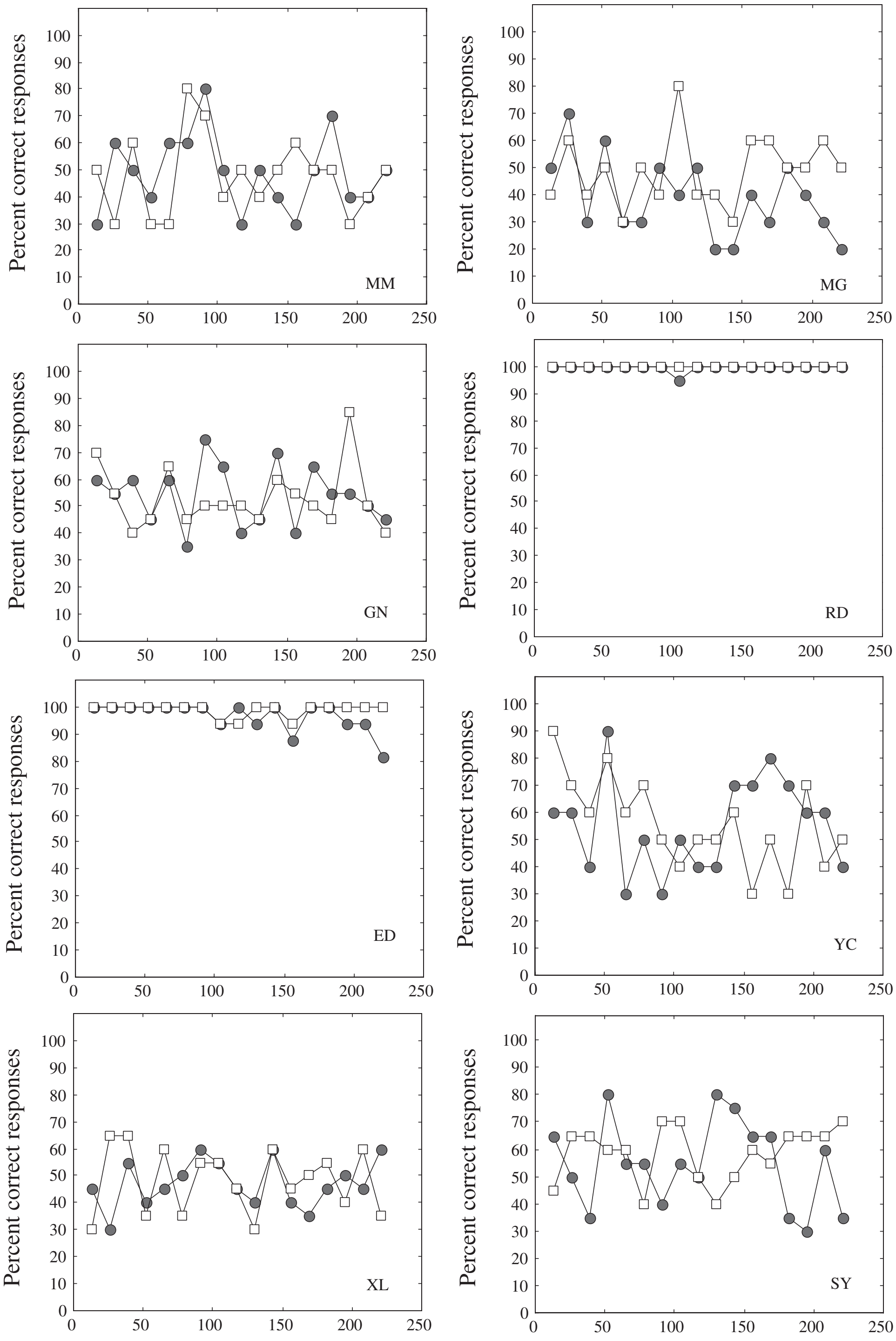

FIGURE 2. Percentage correct as a function of the reciprocal of the temporal frequency (frame durations) for eight amblyopic subjects for temporally correlated (□) and uncorrelated (●) DRSs.

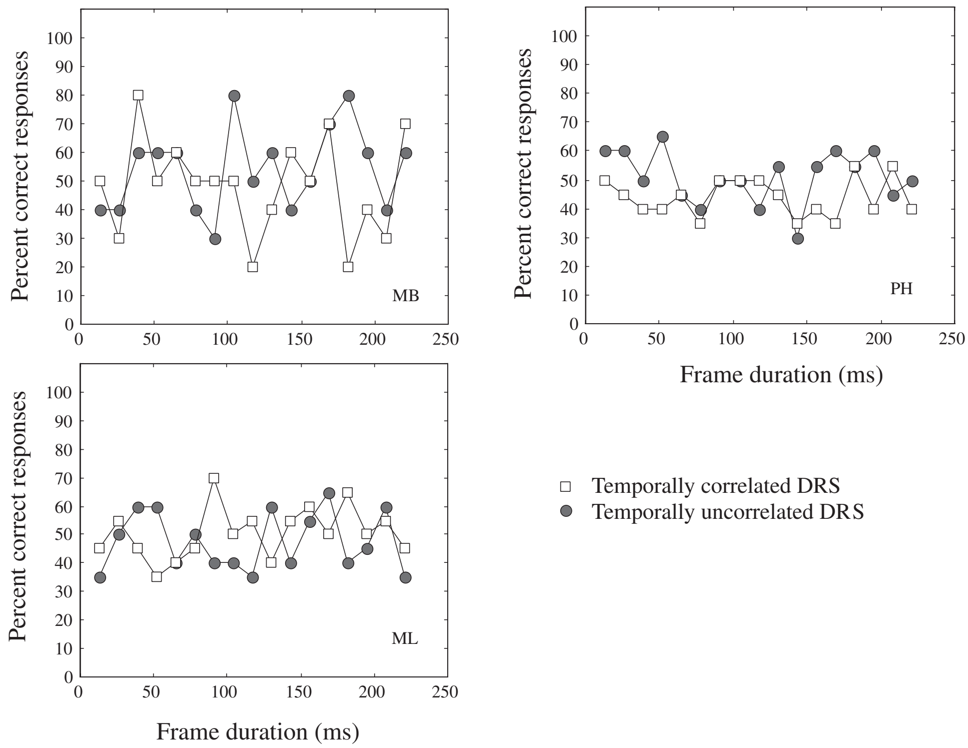

Figure 3. Percentage correct as a function of the reciprocal of the temporal frequency (frame durations) for three amblyopic subjects for temporally correlated and uncorrelated DRSs.

correlated/uncorrelated nature of the stimuli or the temporal frequency. The data from 11 observers with strabismic amblyopia, including the two subjects with stereo function are displayed in Figures 2 and 3 for the temporally correlated and temporally uncorrelated DRSs.

Experiment 2: Effect of the ND Filter

We choose four strabismic subjects whose screening results suggested no stereoscopic function and retested their stereo performance for the temporally correlated and temporally uncorrelated DRSs with an ND filter (density 1.0, with an attenuating effect of a factor of 10) in front of the fellow fixing eye. Our reasoning was to reduce the suppressive influence of the normal eye to test the conjecture that there is latent stereo function in these subjects under these viewing conditions. The individual and group results from these four subjects are shown in Figure 4 for uncorrelated DRSs and Figure 5 for correlated DRSs.

These results are plotted in the same way as described in Figure 2. It is apparent that the application of an ND filter in front of the fixing eye improved the stereo performance in some of the observers with strabismic amblyopia. To test whether the performance was significantly better with the 1-ND filter versus without 1-ND filter with temporally correlated and uncorrelated DRSs, we performed a three-way ANOVA (analysis of variance), with type of DRS (temporally correlated versus temporally uncorrelated DRS), combination (with 1-ND filter vs. without 1-ND filter), and frame duration or temporal frequency (13.3–226 ms) as factors on the data shown in Figures 4b and 5b. The main effect of combination (with versus without 1-ND filter) was significant ($F_{(1,1)} = 254.27$, $P < 0.05$). The effect of temporal frequency was not significant ($F_{(1,16)} = 0.91$, $P > 0.05$; $P = 0.5579$). The effect of type of DRS was also not significant ($F_{(1,1)} = 3.01$, $P > 0.05$; $P = 0.0891$). Thus, the improvement of the group was significant for uncorrelated and correlated DRSs when an ND filter was used.

For comparative purposes, we undertook a similar comparison in four normal subjects, in which the ND filter was placed in front of the dominant eye. These results are shown in Figures 6 (uncorrelated DRS) and 7 (correlated DRS). These results show that the placement of an ND filter in front of one eye reduced stereo performance; again, some subjects were affected more than others. Performance for both correlated and uncorrelated DRSs was reduced.

Experiment 3: Effect of Interocular Delay

It remains a possibility that the reason that stereopsis was not seen when the DRS was used by observers with strabismic amblyopia is that there was a delay between the outputs of the two eyes and that the juxtaposition of an ND filter in front of the fixing eye improves the synchronization of the monocular inputs at the point of binocular combination. Such a timing difference may be also the result of suppression or may have nothing whatsoever to do with suppression. To investigate this possibility, we reassessed stereo performance of our four observers with strabismic amblyopia, but this time with a physical delay between the inputs of the two eyes. This delay varied with the temporal rate, and we wanted to know whether we could mimic the effects we had previously found with the ND filter using stimuli that were simply delayed. We compared uncorrelated DRS (as in Fig. 1a) with uncorrelated delayed DRS (as in Fig. 1c) interleaved within the same run. The results are displayed in Figure 8. Subjects GH and AM exhibited the same baseline performance (Fig. 8) as previously described in Figures 4 and 5, even though these measurements were performed 6 to 9 months apart. For these two subjects, it is clear that a simple delay (Fig. 8) does not in itself improve stereo performance in strabismic eyes. A similar conclusion can be reached for the results of subject KS although baseline measurements (Fig. 8) are worse than measured previously (Figs. 4, 5). The results of subject AR do not bear on this issue, because in the time between the initial measurements

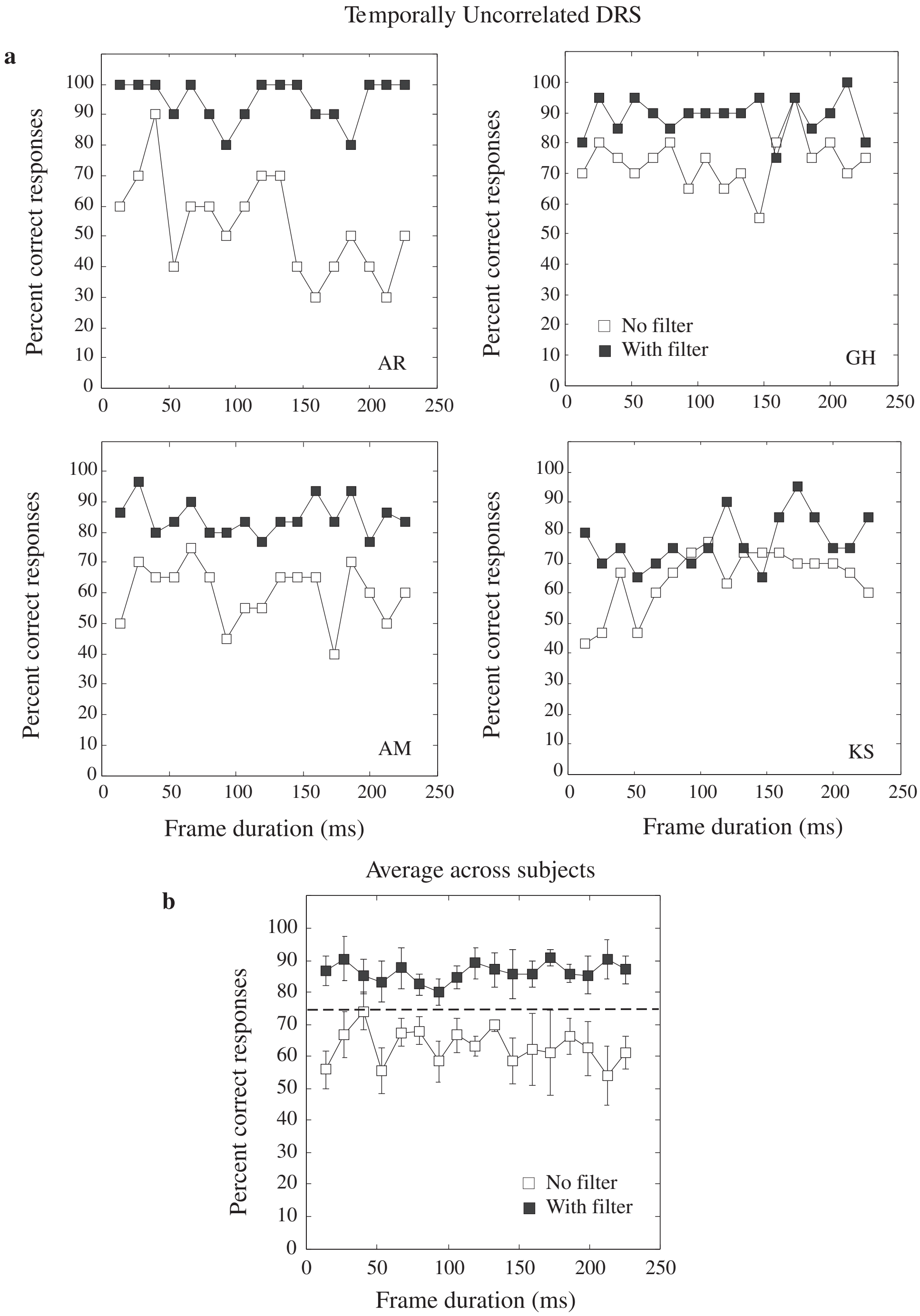

Figure 4. Percentage correct as a function of the reciprocal of the temporal frequency (frame durations) for four strabismic subjects for temporally uncorrelated DRSs, both with and without an ND filter in front of the fixing eye. Individual (**a**) and group (**b**) results are displayed.

(Figs. 4, 5) and the current ones (Fig. 8), he underwent an antisuppression treatment, which resulted in the restoration of binocular fusion with subsequent establishment of static stereopsis.[26] This improvement in static stereopsis (80 seconds, according to the Randot test) also occurred for stereo-in-depth performance (Fig. 8, compare baseline posttreatment performance with previous pretreatment performance in Figs. 4, 5). On the basis of previous results in normal subjects,[27] we were expecting to see an artifactual improvement at the shortest duration (i.e., at the highest repetition rate) as the DRS is perceived to be static at a 50% correlation, a finding present only in the results of amblyopic subject AR for frame durations shorter than 50 ms. Overall, stereo performance was not improved by introducing a time delay across the temporal range, as we had seen previously with the ND filter.

Discussion

Static stereopsis in observers with strabismic amblyopia is rare, but it can occur. The screening data of McKee et al.[28] suggest an incidence of ~2%. It has been reported that a greater fraction of people with strabismic amblyopia exhibit some stereo performance for dynamic stimuli. Rouse et al.[10] report that half of their observers with strabismic amblyopia who were stereoblind to static disparities performed above chance with dynamic stereo stimuli. We found 2 (13%) of 15 cases

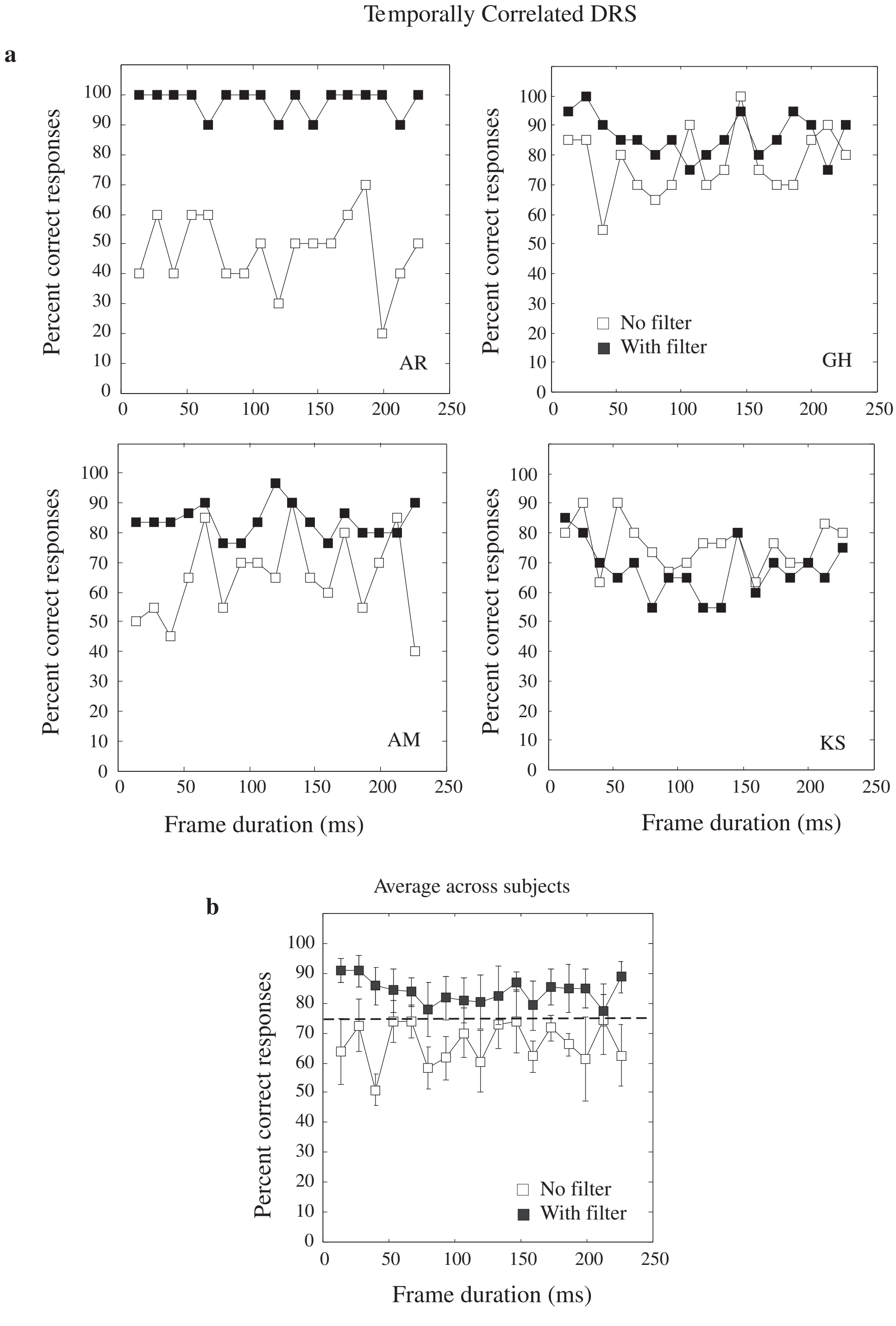

Figure 5. Percentage correct as a function of the reciprocal of the temporal frequency (frame durations) for four strabismic subjects for temporally correlated DRSs, both with and without an ND filter in front of the fixing eye. Individual (**a**) and group (**b**) results are displayed.

from our initial screening (i.e., RD and ED) with motion-in-depth stimuli, and these were the same two individuals who exhibited stereopsis for static stimuli (i.e., the Randot test). Clinically, there was nothing that set these two observers with strabismic amblyopia apart from the other subjects. The task used by Rouse et al. did not involve a depth judgment, and it is possible that velocity-based cues could have determined the above-chance performance that they reported. We set out to use an approach that would specifically address this question. Our task was based on motion in depth and our two stimulus manipulations were designed to answer the question, is any above-chance performance for motion in depth based on interocular velocity differences or disparity differences? Comparing performance for temporally correlated and uncorrelated DRSs allowed us to answer this question, because although both stimuli have disparity-based information, the monocular velocity-based information is disrupted in the temporally uncorrelated DRS. Since we found comparable performance for these two different stimulus manipulations, we conclude that the residual motion in depth performance in these two subjects could not be ascribed to monocular velocity mechanisms. In addition, in four randomly selected cases who did not exhibit above-chance motion-in-depth performance, we found improved stereo performance across all temporal rates tested when an ND filter was put in front of the fixing eye. A similar comparison of static stereopsis using the Randot and TNO

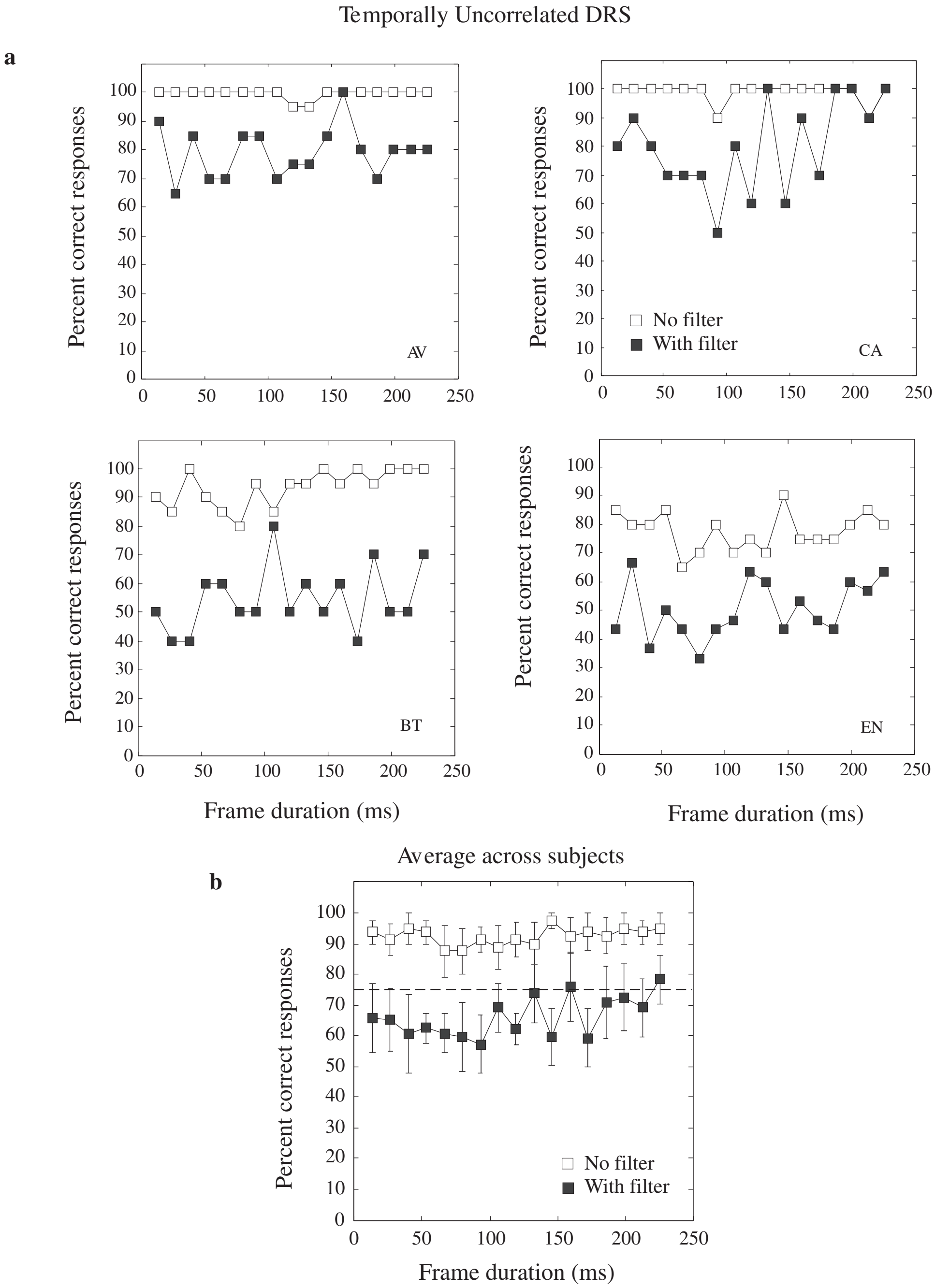

FIGURE 6. Percentage correct as a function of the reciprocal of the temporal frequency (frame durations) for four stereonormal subjects for temporally uncorrelated DRSs, both with and without an ND filter in front of the dominant eye. Individual (**a**) and group (**b**) results are displayed.

stereo tests with and without the ND filter did not reveal any improved stereopsis for any of these four individuals. This suggests a degree of latent stereopsis that is specific for dynamic stimuli in strabismic amblyopia.

Effect of an ND Filter on Contrast and Mean Luminance. It has been shown that persons with strabismic amblyopia have binocular mechanisms, because they exhibit normal levels of binocular contrast summation if the contrast threshold deficit of the amblyopic eye is first accounted for.[14] Furthermore, it has been shown that when the suppression normally exerted by the fellow fixing eye is reduced, suprathreshold information from the two eyes of observers with strabismic amblyopia can be combined normally.[15] A reduction in the interocular contrast is sufficient to effect such a reduction in suppression.[15] All this argues for there being intact binocular hardware within the visual cortex of observers with strabismic amblyopia that is rendered functionally monocular due to active suppression. More recently, we have shown that suppression results in a reduction in the perceived mean luminance by the amblyopic eye rather than a reduction in contrast perception (Maehara G et al., manuscript in preparation) and that the suprathreshold deficit for contrast discrimination in amblyopia can be modeled by a normal eye viewing through an ND filter.[29] With the stimuli used in the present study, an ND filter will reduce both the contrast and the mean luminance since they were displayed as bright elements on an otherwise dark background. Therefore, the beneficial effects of placing an ND filter in front of the fixing eye is likely to be the result of reducing the fixing eye's suppressive influence via a reduction in contrast, mean luminance, or both.

Effect of an ND Filter on Timing. The effect of an ND filter placed over one eye is also to introduce an interocular

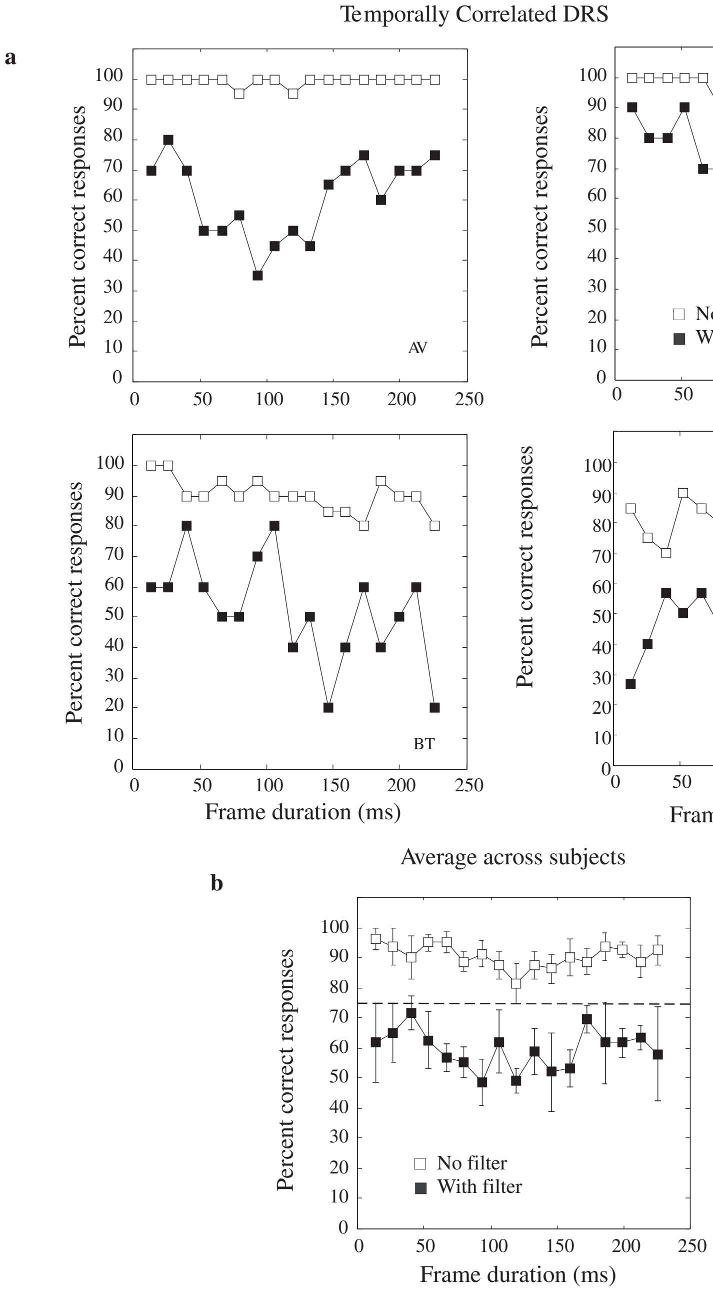

Figure 7. Percentage correct as a function of the reciprocal of the temporal frequency (frame durations) in four stereonormal subjects for temporally correlated DRSs, both with and without an ND filter in front of the fixing eye. Individual (**a**) and group (**b**) results are displayed.

delay between the signals to the two eyes. Several studies have been undertaken to investigate the effects of interocular delays in normal subjects,[30–32] and the reports have shown that the stereoscopic system tolerates a time difference between binocular correlated random-dot images of up to 50 ms. Using DRSs, Julesz and White[30] investigated the delay hypothesis and reported that a disparity-defined square of 48 arcmin was not perceived with one frame delay (~80 ms). Cumming and Read[33] recorded responses of disparity-selective V1 neurons using DRSs in which each image was refreshed for every frame and showed that an interocular delay of only one video frame (14 ms) reduced dramatically the magnitude of the disparity-selective response. Using different DRSs consisting of continuous alternation of two image pairs, Gheorghiu and Erkelens[27] showed that disparities from simultaneously presented monocular inputs dominate those from interocularly delayed inputs and thus, interocular time delays between correlated images are hardly tolerated in the visual system.

To address whether the reason that stereopsis is not seen using DRS in observers with strabismic amblyopia is because there is a delay between the two eye's outputs and that the juxtaposition of an ND filter in front of the fixing eye improves the synchronization of the monocular inputs at the point of binocular combination, we reassessed stereo performance for our four observers with strabismic amblyopia, but this time with a delay between the two eyes' inputs. This delay varied with the temporal rate, and we wanted to know whether we could mimic the effects we had previously found with the ND filter using stimuli that were simply delayed. We compared uncorrelated DRS (as in Fig. 1a) with uncorrelated delayed DRS (as in Fig. 1c) interleaved within the same run. The results (Fig. 8) show that this explanation is not tenable, as stereo performance was not improved as we had seen previously for the ND filter by introducing a time delay across the temporal range.

In conclusion, along with other researchers,[9–11] we have found that stereo performance for motion-in-depth stimuli is

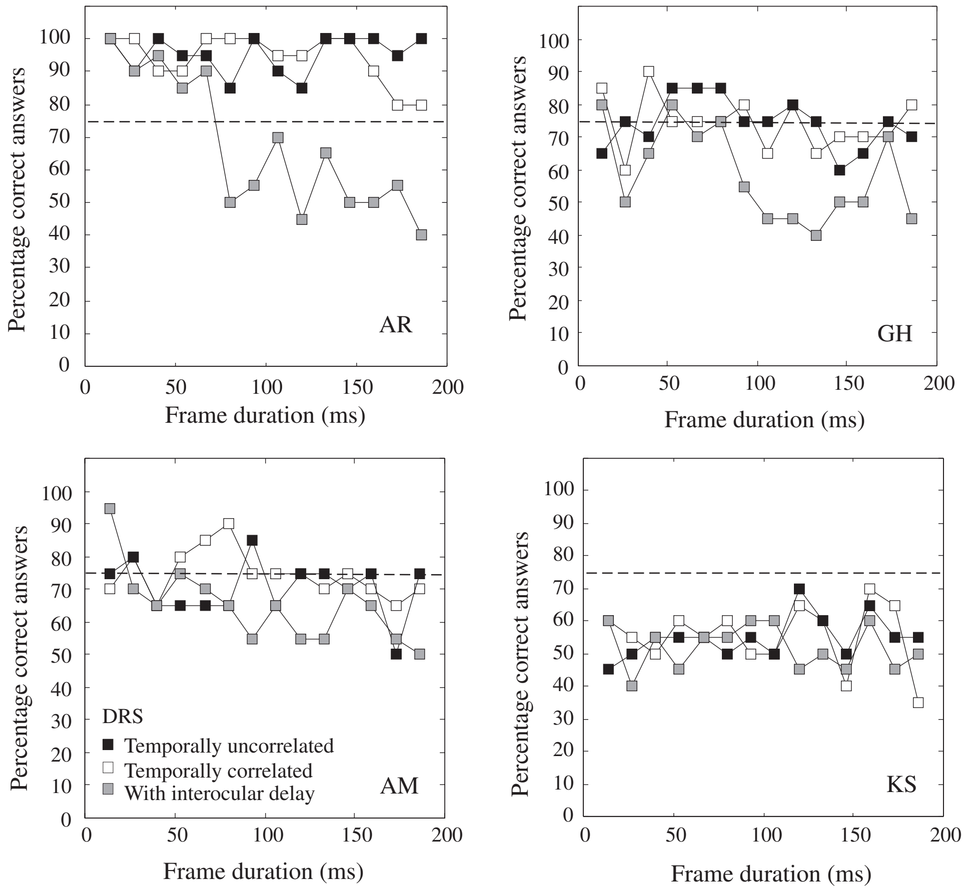

FIGURE 8. Percentage correct performance for correlated and uncorrelated motion-in-depth stimuli, with and without a temporal delay that scaled with temporal frequency. The results were obtained by temporally interleaving these three conditions within the same run in four observers with strabismic amblyopia.

possible in strabismic amblyopia although we found it in the same individuals who exhibited static stereopsis (i.e., RD and ED). Above-chance performance for motion-in-depth stimuli does not depend on the temporal rate, and it is based on disparity detection not monocular velocity detection. In cases in which it is not present under normal binocular viewing, it may be revealed under conditions in which suppressive influences of the fellow fixing eye are reduced. This can be produced by interocular reductions of contrast and mean luminance. The use of an ND filter can be beneficial. These results suggest that in some cases of strabismic amblyopia (all the cases studied here were of microstrabismus except two), there is a latent stereopsis for dynamic stimuli. Our use of stimuli of fixed disparities does not permit us to speculate about the range of disparities over which this latent stereopsis operates nor on the relationship between the size of suppression scotomata and residual motion-in-depth performance.

References

1. Baker F, Grigg P, von Noorden G. Effects of visual deprivation and strabismus on the response of neurons in the visual cortex of the monkey, including studies of striate and prestriate cortex in the normal animal. *Brain Res.* 1974;66:185–208.
2. Bennett MJ, Smith EL 3rd, Harwerth RS, Crawford ML. Ocular dominance, eye alignment and visual acuity in kittens reared with an optically induced squint. *Brain Res.* 1980;193:33–45.
3. Hubel DH, Wiesel TN. Binocular interaction in striate cortex of kittens reared with artificial squint. *J Neurophysiol.* 1965;28:1041–1059.
4. Levi DM, Harwerth RS, Smith EL 3rd. Observers deprived of normal binocular vision have binocular interactions tuned to size and orientation. *Science*. 1979;206:852–854.
5. Levi DM, Harwerth RS, Smith EL 3rd. Binocular interactions in normal and anomalous binocular vision. *Doc Ophthalmol*. 1980;49:303–324.
6. Vedamurthy I, Suttle CM, Alexander J, Asper LJ. Interocular interactions during acuity measurement in children and adults, and in adults with amblyopia. *Vision Res.* 2007;47:179–188.
7. Cooper J, Feldman J. Random-dot-stereogram performance by strabismic, amblyopic, and ocular-pathology patients in an operant-discrimination task. *Am J Optom Physiol Opt.* 1978;55:599–609.
8. Cynader M, Gardner JC, Mustari M. Effects of neonatally induced strabismus on binocular responses in cat area 18. *Exp Brain Res.* 1984;53:384–399.
9. Kitaoji H, Toyama K. Preservation of position and motion stereopsis in strabismic subjects. *Invest Ophthalmol Vis Sci.* 1987;28:1260–1267.
10. Rouse MW, Tittle JS, Braunstein ML. Stereoscopic depth perception by static stereo-deficient observers in dynamic displays with constant and changing disparity. *Optom Vis Sci.* 1989;66:355–362.
11. Sireteanu R, Fronius M, Singer W. Binocular interaction in the peripheral visual field of observers with strabismic and anisometropic amblyopia. *Vision Res.* 1981;21:1065–1074.
12. Mower GD, Christen WG, Burchfiel JL, Duffy FH. Microiontophoretic bicuculline restores binocular responses to visual cortical neurons in strabismic cats. *Brain Res.* 1984;309:168–172.
13. Sengpiel F, Jirmann K-U, Vorobyov V, Eysel U. Strabismic suppression is mediated by interactions in the primary visual cortex. *Cerebral Cortex.* 2006;16:1750–1758.
14. Baker DH, Meese TS, Mansouri B, Hess RF. Binocular summation of contrast remains intact in strabismic amblyopia. *Invest Ophthalmol Vis Sci.* 2007;48:5332–5338.
15. Mansouri B, Thompson B, Hess RF. Measurement of suprathreshold binocular interactions in amblyopia. *Vision Res*. 2008;48(28):2775–2784.

16. Cumming BG. The relationship between stereoacuity and stereomotion thresholds. *Perception.* 1995;24:105–114.
17. Cumming BG, Parker AJ. Binocular mechanisms for detecting motion-in-depth. *Vision Res.* 1994;34:483–495.
18. Lages M, Mamasian P, Graph EW. Spatial and temporal tuning of motion in depth. *Vision Res.* 2003;43:2861–2873.
19. Norcia AM, Tyler CW. Temporal frequency limits for stereoscopic apparent motion processes. *Vision Res.* 1984;24:395–401.
20. Regan DM. Binocular correlates of the direction of motion in depth. *Vision Res.* 1993;33:2359–2360.
21. Tyler CW. Stereoscopic depth movement: two eyes less sensitive than one. *Science.* 1971;174(12):958–961.
22. Gheorghiu E, Erkelens CJ. Differences in perceived depth for temporally correlated and uncorrelated dynamic random-dot stereograms. *Vision Res.* 2005;45:1603–1614.
23. Regan D, Beverley KI. Binocular and monocular stimuli for motion in depth: changing disparity and changing size feed the same motion-in-depth stage. *Vision Res.* 1979;19:1331–1342.
24. Regan DM, Beverley KI, Cynader M. Separate subsystems for position in depth and for motion in depth. *Proceed Roy Society London B.* 1979;204:485–501.
25. Shioiri S, Saisho H, Yaguchi H. Motion in depth based on interocular velocity differences. *Vision Res.* 2000;40:2565–2572.
26. Mansouri B, Thompson B, Hess RF. Improvements in binocular vision following a new binocularly-based treatment for amblyopia (abstract). *Abstract. Washington, DC: Society for Neuroscience: 2008:Program 454.4.*
27. Gheorghiu E, Erkelens CJ. Temporal properties of disparity processing revealed by dynamic random-dot stereograms. *Perception.* 2005;34:1205–1219.
28. McKee SP, Levi DM, Movshon JA. The pattern of visual deficits in amblyopia. *J Vis.* 2003;3:380–405.
29. Baker DH, Meese TS, Hess RF. Contrast masking in strabismic amblyopia: attenuation, noise, interocular suppression and binocular summation. *Vision Res.* 2008;48(15):1625–1640.
30. Julesz B, White B. Short term visual memory and the Pulfrich phenomenon. *Nature.* 1969;222:639–641.
31. Mitchell DE, O'Hagan S. Accuracy of stereoscopic localization of small line segments that differ in size or orientation for the two eyes. *Vision Res.* 1972;12:437–454.
32. Ross J, Hogben JH. Short-term memory in stereopsis. *Vision Res.* 1974;14(11):1195–1201.
33. Cumming BG, Read JC. Effect of interocular delay on disparity-selective v1 neurons: relationship to stereoacuity and the pulfrich effect. *J Neurophysiol.* 2005;94:1541–1553.